Comprehensive Scientific Program for a Deep Underground Massive Neutrino Detector and an Intense Long-Baseline Neutrino Beam

authors

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Abstract

Abstract.

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1 Prologue

Particle physics has been very successful in creating a major synthesis of its findings, the Standard Model. At successive generations of particle accelerators in the US, Europe and Asia, physicists have used high-energy collisions to discover many new particles. By studying these particles, they have uncovered both new principles and many unsuspected features of nature, resulting in a detailed and comprehensive picture of the workings of the universe.

While the Standard Model is still incomplete, recent revolutionary discoveries have shown that it represents a good approximation at the energies of existing accelerators. A striking development in neutrino physics, thanks to a remarkably broad suite of experiments, is the discovery that the three kinds, or "flavors," of neutrinos (each associated with a partner lepton: electron, muon or tau), all previously thought massless, do in fact have small masses and can transform from one flavor to another. The Standard Model has evolved to accommodate these findings.

These properties imply that neutrinos play critical roles across many fields of physics and make them uniquely suitable as probes.**FIXME:** *why, exactly?*

Neutrinos have shown us details of the solar core, provided clues to the mechanism of supernova explosions, and most likely play an important role in the early universe. They may even hold the key to understanding the observed preponderance of matter over antimatter.

In the current leading explanation of matter-antimatter asymmetry, *leptogenesis*, decays of very heavy right-handed neutrinos into baryons in the early universe give rise to a lepton number asymmetry that later becomes a baryon-antibaryon asymmetry. Leptogenesis offers an elegant, natural explanation for the observed matter-antimatter asymmetry, but it still requires experimental confirmation of its various components. These include the existence of very heavy right-handed neutrinos as well as lepton number asymmentry and CP violation in their decays.

Understanding neutrinos may help us answer some of the most fundamental physical questions concerning the origins of matter and of our very existence:

- Why is the universe as we know it made of matter, with no antimatter present? Why didn't the matter and antimatter annihilate each other completely?
- How are neutrinos connected to this asymmetry?
- What role did neutrinos play in the evolution of the universe?
- What is the role of neutrinos in the dynamics of stars and formation of heavy atoms?
- What is the nature of new particles and new principles beyond the Standard Model?

Predicted by Wolfgang Pauli as nothing more than a 'desperate way out' of the puzzling behavior of electrons created in beta-decay, neutrinos have turned out to be far more complex—and important—than he could have imagined.

2 LBNE Vision and Physics Goals

2.1 Primary Physics Goals

LBNE proposes to conduct a comprehensive study of the physics of neutrino oscillation, focusing primarily on the search for CP violation in the neutrino sector. The magnitude of CP violation depends on the parameters that govern neutrino oscillation, therefore we aim to determine the values of the remaining unknown oscillation parameters, namely, the mixing and phase angles θ_{13} and δ_{CP}, respectively, and the sign of Δm^2_{32}.

2.2 Scope and Strategy

To measure these quantities, LBNE will require an experimental setup at least an order of magnitude (factor of ten) more sensitive than the experiments that will begin to acquire data in the next few years. The US program may be uniquely positioned to achieve this sensitivity given the requisite separation of an intense neutrino beam source and a detector. Fermi National Accelerator Laboratory (FNAL) is poised to host the accelerator, and 1300 km away, an old gold mine in South Dakota has caverns large enough to accommodate the necessary detectors at a level deep enough to significantly suppress backgounds.

The lessons learned over the past decade about how to build and operate large neutrino detectors and intense neutrino beams, combined with the creation of the Deep Underground Science and Engineering Laboratory (DUSEL) in the Homestake Mine in Lead, South Dakota, have given rise to a remarkable new opportunity. It is now possible to design and implement practical experiments to measure the parameters that characterize three-generation neutrino oscillations and **FIXME:** *"the postulated"?* CP violation, for a significant range of parameter values beyond present limits.

LBNE proposes to build a new neutrino beam at FNAL, in Batavia, Illinois, and a multi-hundred kiloton, underground, Water Cherenkov-equivalent particle-tracking detector at the Homestake Mine in Lead, South Dakota. We expect the construction of these facilities to provide a rich, world-leading physics program that would last for decades.

FIXME: *have the LAr people review this – doesn't account for possbile shallower depth* Planning for DUSEL anticipates several large caverns, with diameter and height of > 50 m, at depth of 4850 feet, **FIXME:** *do we want m and ft in same sentence?* each capable of housing a 100-150 kiloton water Cherenkov detector. Other large cavities at DUSEL could house one or more liquid argon time projection chambers, an alternate technology with the potential to deliver better performance per unit mass. Placing these detectors deep underground, thereby shielding them from cosmic ray backgrounds, will expand the physics scope by significantly improving our ability to observe nucleon decay and natural sources of neutrinos.

2.3 The Wider Physics Program

The apparatus and infrastructure required for the proposed experiment lend themselves to a wider, multi-pronged experimental program, including a further study of oscillation using neutrinos from the sun and the atmosphere, the search for proton decay, the observation of supernova bursts in or near our galaxy and relic neutrino fluxes of supernovae from much farther away. In particular, our goals from these additional studies will likely include:

- A sensitive search for nucleon decay to find out if the proton is stable,
- Increased sensitivity to atmospheric neutrinos allowing more precise measurement of the neutrino mixing parameters,
- Detection of neutrino bursts from exploding nearby supernovae, with sensitivity that could go as far as the Andromeda galaxy and may coincide with optical observation,
- Observation of 'relic' neutrinos left over from the supernovae that have occurred throughout the history of our galaxy,
- A search for the predicted 'day/night' asymmetry in the intensity of electron neutrinos from the sun (current theory suggests a higher content of electron-type solar neutrinos passing through the Earth at night relative to during the day), and
- A search for astrophysical sources of high-energy neutrinos.

2.4 Detector Technologies

2.4.1 Water Cherenkov

A charged particle traveling through transparent material, with a speed exceeding the speed of light in that material, generates *Cherenkov light* in a cone around the particle's direction of travel. Water Cherenkov detectors (WCDs), massive water containers instrumented with light-collection devices, exploit the phenomenon of Cherenkov light emission to detect evidence of particle interactions. Water provides an abundant, inexpensive and easy-to-handle target material. The cone of Cherenkov light travels through the clear water volume and arrives at the container wall, where it produces a ring pattern detected by the photomultiplier tubes (PMTs) lining the container walls. We use the PMT readouts to (1) determine the arrival time and the number of photons produced by the Cherenkov radiation and (2) uniquely reconstruct the geometry (vertex, direction and ending point) of the particles path. This information allows us to estimate the particles energy and identify its type. **FIXME:** *(Figure 3 of Depth doc)*. A highly relativistic particle of unit elementary charge traveling in water will generate several hundred Cherenkov photons in the wavelength range of PMT sensitivity per centimeter of travel.

As a technology for massive detectors, WCDs offer the advantages of low cost, relative simplicity of design and ease of operation.

To enhance LBNE's ability to detect neutrinos from supernov, we are studying the addition of a water- soluble gadolinium (Gd) compound: gadolinium chloride, $GdCl_3$, or the less reactive though also less soluble gadolinium sulfate, $Gd_2(SO_4)_3$. Neutron capture on hydrogen yields a 2.2 MeV gamma, which is essentially invisible in plain light-water detectors, however on gadolinium the interaction produces a visible 8.0 MeV gamma cascade. The inverse beta decay reaction,

$$\overline{\nu}_e + p \rightarrow e^+ + n \tag{1}$$

in such a Gd-enriched detector will yield coincident positron and neutron capture signals as long as the detector has sufficient light collecting power (i.e., will record five or more photoelectrons per MeV). This will greatly reduce backgrounds and enhance the detector's response to both supernova neutrinos (galactic and relic) and reactor antineutrinos **FIXME:** *[**?**] add vagins_gadzooks ref.*

By adding 0.1% Gd by mass to the water, the gadolinium would visibly catch slightly over 90% of the inverse beta neutrons. In a 300 kton detector, this requires 300 tons of gadolinium – about 600 tons of $GdCl_3$ or $Gd_2(SO_4)_3$. Due to recent breakthroughs in the price of gadolinium **FIXME:** *ref?*, this would cost no more than $6,000,000 for either compound, adding about 1% to the capital cost of detector construction.

2.4.2 Liquid Argon

A liquid argon time projection chamber (LArTPC) detects neutrinos via the outgoing charged particles that result from neutrino interactions with ultra-pure liquid argon. A strong, uniform electric field within the detector carries electrons from passing charged particles through the liquid argon to the edge of the detector. The electric potentials of three wire chamber readout planes in the detector are arranged such that the electrons pass through the first three **FIXME:** *two?* (induction) planes to a third (collection) plane. These readout planes record the position and time of the passing charge. The amplitude of the ionization electron signals indicates the energy loss of the particles, which allows an estimate of their momenta and particle types. From this information, the LArTPC records a three-dimensional "photo-like" image of the passing particle tracks along with the energy deposited by them. The few-millimeter-scale spatial granularity of an LArTPC combined with energy information at each step make it a very powerful detection technique. **FIXME:** *there's a pic in depth doc*

LArTPC technology offers some extraordinary capabilities:

- Precise differentiation of electrons versus photons in events,
- High resolution for reconstruction of particles in events, including nuclear debris, and

- Quick data processing due to fast operation and direct production of electronic signals

3 Neutrino Oscillation Physics

3.1 Overview

Over the past few decades, scientists have observed changes in atmospheric muon-neutrinos and solar electron-neutrinos, from one flavor to another, between their source and detection. Further experimentation with both natural neutrino sources and neutrinos from reactors and accelerators has confirmed that the flavor states do not remain constant in time.

A neutrino, like a photon, propagates with a given frequency. For a neutrino, the frequency is associated with its mass. A neutrino's mass governs how it propagates in space, but its flavor (ν_e, ν_μ or ν_τ) governs how it interacts with (couples to) other neutrinos and other particles. Analogous to a pair of lightly-coupled, orthogonal harmonic oscillators of differing frequencies, a pair of coupled neutrinos propagating with different frequencies will precess in a quantum-mechanical phase space. As they precess, they will pass through pure ν_e, ν_μ or ν_τ states (depending on their original flavors) as well as through states that are mixtures of these; the mixed states are called ν_1, ν_2 and ν_3. These quantum-mechanical mixings of (pure) flavor states propagate differently according to the relative flavor proportions: this phenomenon is called *neutrino oscillation*.

3.2 Brief History and Status

FIXME: *the following is from arxiv 0410090v1 (not yet edited (except for some of the math symbols) by Anne)*

The first idea of neutrino masses, mixing and oscillations was suggested by B.Pontecorvo in 1957 [B. Pontecorvo, J.Exptl. Theoret. Phys. 33 (1957) 549 [Sov. Phys. JETP 6 (1958) 429].]. He thought that there is an analogy between leptons and hadrons and he believed that in the lepton world exist phenomenon analogous to the famous $K_0 K_0$ oscillations.

The only possible candidate were neutrino oscillations. At that time only one neutrino type was known. The evidence of neutrino oscillations was obtained in the atmospheric Super–Kamiokande experiment [1], in the solar SNO experiment [2] in the reactor KamLAND experiment [3], and also in solar neutrino experiments [4, 5, 6, 7], atmospheric neutrino experiments [8, 9], and in the first long baseline accelerator K2K experiment [10].

Today all existing neutrino oscillation data with the the exception of the data of LSND experiment [LSND Collaboration, A. Aguilar et al., Phys.Rev.D64 (2001) 112007; hep-ex/0104] are described by the three-neutrino mixing. For neutrino oscillation parameters the following values were obtained **FIXME:** *see refs below [1, 3, 41]*: **FIXME:** *These were entered with non-ascii characters and some things are unknown as to what was being written.* $\Delta m^2 = (8.2 \pm 0.6) \times 10^5 eV^2$; $\tan 2\theta = (0.40 \pm 0.09) 21 - 0.512 - 0.07$; $1.9 \times 10^{-3} \leq \Delta m^2_{32} \leq 3.0 \times 10^3 eV^2$; $\sin^2 2\theta_{23} \geq 0.90$; $\sin^2 \theta_{13} \leq 5 \times 10^{-2}$. Thus, neutrino oscillation parameters satisfy inequalities $\Delta m^2_{21} << \Delta m^2_{32}; \sin^2 \theta_{13} << 1$ It follows from

(32) (see [42]) that the dominant transitions, governed by δm^2_{32}, are $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$. Dominant transitions, governed by Δm^2_{21}, are $\nu_e \to \nu_{\mu,\tau}$ and $\bar{\nu}_e \to \bar{\nu}_{\mu,\tau}$. This is a present-day picture of neutrino oscillations.

[1] Super–Kamiokande Collaboration, S. Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998); S. Fukuda et al., Phys. Rev. Lett. 82, 2644 (1999); S. Fukuda et al., Phys. Rev. Lett. 85, 3999-4003 (2000). E. Kearns Proceedings of 21th International Conference on Neutrino Physics and Astrophysics (Neutrino 2004), 13-19 June 2004, Paris, France. [3] KamLAND Collaboration, T. Araki et al hep-ex/0406035, submitted to Phys.Rev.Lett. [41] CHOOZ Collaboration, M. Apollonio et al., Phys. Lett. B 466 415 (1999). [32] S.M. Bilenky and B. Pontecorvo, Lett. Nuovo Cim. 17 (1976) 569. [42] S. M. Bilenky , C. Giunti and W. Grimus, Prog.Part.Nucl.Phys. 43 (1999) 1; hep-ph/9812360.

FIXME: *end arxiv 0410090v1; add table of known ν osc param's here.*

From measurements of solar and reactor neutrino oscillations, scientists have found that $\Delta m^2_{21} \simeq 8 \times 10^{-5}\text{eV}^2$ and $\theta_{12} \simeq 32°$**FIXME:** *(update numbers; new number for sin sqd is .87 +/-.03, but this yields theta of about 70 degrees – way different from 32. Delta m sqd same to this sigfig, 7.59 +/- .20).* **FIXME:** The positive sign of Δm^2_{21}, mentioned above, follows from the effects of the solar medium on the propagation.**FIXME:** *how?*

3.3 Scientific Interest

With the discovery of neutrino oscillation, physicists have built a model of neutrinos resembling that in the quark sector, in which three nonmassless neutrino flavors transform into one another (mix) according to a mathematical construct called a mixing matrix. The mass states are mixtures of the pure flavor states. **FIXME:** *add figure of mixing matrix here*

Experiments at Super–Kamiokande in Japan have demonstrated that muon neutrinos from the atmosphere change into tau neutrinos on their way to the surface of the earth, an experimental result explained by the fact that neutrinos have mass, albeit some 100 million times smaller than the electron's. The so-called See-Saw mechanism, which seems to most naturally explain this phenomenon, posits that the neutrino is *light* as a consequence of a very *heavy* new energy scale $M \sim 10^{10}$ to 10^{14} GeV, with $m_{\text{neutrino}} \sim (m_{\text{lepton}})^2/M$. This fits in well with Grand Unified Theories (GUTs), which unify the strong, weak and electromagnetic interactions at a similar energy scale. Thus a study of neutrino mass and oscillationas may be a window onto this large energy scale.

3.3.1 CP Violation

Does a neutrino behave in the same way as an antineutrino and as its own mirror image, respectively? If not, it is said to "violate CP". Measurable CP violation in the lepton sector is a necessary component of explaining why matter behaves differently from antimatter, why matter is dominant over antimatter, and the overall role of CP violation in nature. CP violation has so far only been observed in the quark sector, but at such a weak level that it cannot account for the observed asymmetry.

3.3.2 The Unknown Neutrino Mixing Parameters: θ_{13} and δ_{CP}

The quantum mechanical neutrino mixing is parameterized by three mixing angles, θ_{12}, θ_{23} and θ_{13} and one phase angle, δ_{CP}, called the *CP phase.* The angle δ_{CP} describes how neutrinos and antineutrinos differ in their behaviors and its value will indicate the strength of CP violation. If it is zero, CP violation doesn't exist in the neutrino sector.

The first two mixing angles are known; see table 1. Currently, we know nothing about the value of the δ_{CP} and only have an upper bound on the mixing angle θ_{13}.

Parameter	Measured Value or Limit
$\sin^2 2\theta_{12}$	0.87 ± 0.03
Δm^2_{21}	$(7.59 \pm 0.20)10^{-5}eV^2$
$\sin^2 2\theta_{23}$	> 0.92
$\lvert\Delta m^2_{32}\rvert$	$(2.43 \pm 0.13)10^{-3}eV^2$
$\sin^2 2\theta_{13}$	< 0.19, CL=90%

Table 1: Values of known neutrino oscillation mixing parameters.

The strength of the mixing depends on the product of the mixing angles and on the difference in the squares of the masses ($\Delta m^2_{ba} = m^2_b - m^2_a$) of the participating neutrinos. The mixing angles θ_{12} and θ_{23} are large relative to the mixing angles in the quark sector (we don't yet understand why). The neutrino masses, however, are more than seven orders of magnitude smaller than the smallest quark mass. These differences could be clues to physics beyond the Standard Model. Measuring the as-yet-unknown θ_{13} is critical to this pursuit. In addition, the fact that θ_{23} is near maximal is also interesting; measuring it with greater precision is highly desirable.

An inclusive survey of 63 models in the literature found predictions for θ_{13} clustered around $\sin^2 2\theta_{13} = 0.04$ ($\sin^2\theta_{13} = 0.01$), as displayed in Fig. 3.3.2. If $\sin^2 2\theta_{13}$ is in fact comparable to or greater than this value, we are likely to determine it by the coming generation of reactor $\bar{\nu}_e$ disappearance experiments at Double Chooz (France), RENO (South Korea) and Daya Bay (China), as well as the upcoming accelerator-based $\nu_\mu \to \nu_e$ appearance experiments T2K (Japan, beam from J-PARC to Super–Kamiokande) and NOνA (US, beam from FNAL to Minnesota). Reactor experiments are complementary to long-baseline experiments in that they can provide valuable information on θ_{13} independent of other parameters. Accelerator experiments measure θ_{13} in a way that depends on other physics, such as the neutrino mass levels and CP violation.

Unlike all of the other known fundamental fermions (half-integer spin particles that obey Fermi-Dirac statistics, e.g., quarks and leptons), neutrinos may be *Majorana fermions*, particles that are their own antiparticles. If this is the case,

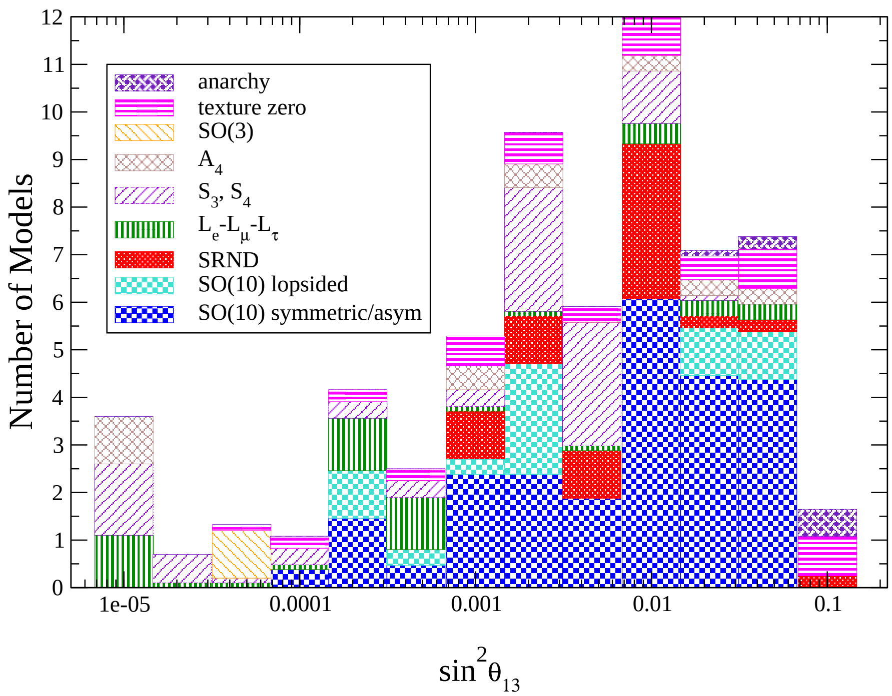

Figure 1: Histogram of $\sin^2\theta_{13}$ predictions for 63 models. Source: C.H. Albright and M.C. Chen, arXiv:hep-ph/0608137.

two additional (otherwise nonexistent) phases may be added to the model, for a total of nine free parameters, including the neutrino masses. The set of neutrino masses, mixings and phases is a fundamental and rich dynamical system with many potential experimental consequences that we are only just beginning to explore.

3.3.3 The Mass Hierarchy

The discovery of atmospheric neutrino oscillations in the Super–Kamiokande experiment demonstrated that $\Delta m^2_{32} \simeq \pm 2.5 \times 10^{-3}\mathrm{eV}^2$ and mixing angle $\theta_{23} \simeq 45°$. The MINOS experiment has confirmed and honed these findings (see table 1) with an accelerator-generated neutrino beam from Fermilab directed at a detector in the Soudan mine in Minnesota.

The sign of Δm^2_{21} is known to be positive, however, as yet the sign of Δm^2_{32} is undetermined. The so-called normal mass hierarchy, $m_1 < m_2 < m_3$, suggests a positive sign, however a negative value (or inverted hierarchy, $m_1 > m_2 > m_3$) is also possible, and would likely predict larger rates for neutrinoless double beta decay (see equation 2.4.1) that are easier to access experimentally.

A number of neutrino mass models have been proposed and precise knowledge of neutrino mixing parameters is essential to test them. Specifically, the value of the mixing angle θ_{13} and the trend of the mass hierarchy (normal or inverted) will help distinguish between models based on neutrino or other lepton flavor symmetries, models with sequential right-handed neutrino dominance (contrary to current observations that indicate left-handed dominance, referring to the anti-alignment of a neutrino's spin and its momentum vector), and more ambitious models based on Grand Unified Theory (GUT) symmetries.

The closer together the three Δm^2 values fall, the easier it will be to see CP violation. The quantity Δm^2_{21} is about 30 times smaller than $|\Delta m^2_{32}|$, close enough to make long-baseline neutrino oscillation searches for CP violation feasible.

3.4 Long-Baseline Experimental Goals

Scientists around the world have initiated a new generation of experiments using reactor and accelerator neutrinos to make precise measurements of neutrino mixing phenomena. LBNE's goals are similar, but reach farther and require greater sensitivity:

- Measure δ_{CP} to determine if CP violation occurs in the lepton sector,
- Determine precisely the known mixing parameters, in particular $\sin^2 2\theta_{13}$, with sensitivity down to 1%,
- Determine the sign of Δm^2_{32},
- Search for exotic effects in neutrino oscillations, and
- Look for physics beyond the modified Standard Model (that now includes massive neutrinos).

The US long-baseline neutrino research complex we envision would provide an extraordinary opportunity to achieve our primary objectives with unprecedented sensitivity.

3.5 Long-Baseline Experimental Considerations

The proposed long-baseline neutrino oscillation studies require a large flux of neutrinos, created by an intense 1-2 MW proton beam, to strike a very large-volume detector capable of identifying electron- neutrino interactions. Potential LBNE detectors include a multi-hundred kt Water Cherenkov detector or a $\sim$ 100 kt liquid argon TPC detector, likely equivalent in sensitivity due to its better performance per unit mass. This represents an increase in sensitivity of more than an order of magnitude over the experiments currently under construction.

FIXME: *a sentence about how many neutrinos we need to see per unit time, per unit mass, whatever. Justify this requirement of intense beam into large detector.*

Water Cherenkov is an established neutrino detector technology, while liquid argon, which promises superior particle identification and control over backgrounds **FIXME:** *due to its xyz properties*, is still under development.

Due to the variability in the probability of measuring ν_e versus $\bar{\nu_e}$ with baseline distance, siting the detector more than 1000 km from the neutrino beam source will enhance our ability to measure the amount of CP violation, the neutrino oscillation parameters and the mass hierarchy via $\nu_\mu \rightarrow \nu_e$ appearance studies. The optimal baseline for a wide-band (on-axis) beam experiment is between 1000 and 1500 km.**FIXME:** *ref?*

FIXME: *Need to add missing figure figures/lumiSummary*

Figure 2: **FIXME:** *Milind will find updated figure* The $\sin^2 2\theta_{13}$ reach at 3σ for the discovery of nonzero $\sin^2 2\theta_{13}$, CP violation, and the normal hierarchy as a function of exposure. The curves are for a fraction of δ_{CP} of 0.5, which means that the performance will be better for 50% of all values of δ_{CP}, and worse for the other 50%. The light curves in the CPV panel are made under the assumption that the mass hierarchy is known to be normal. The dots mark the exposures of the setups as defined in Table **??**. The shaded regions result by varying the systematic uncertainties from 2% (lower edge) to 10% (upper edge).

3.6 Solar and Atmospheric Neutrino Oscillation Studies

Lower priority, yet still interesting, studies to undertake include solar and atmospheric neutrino oscillations. Solar and atmospheric neutrinos interacting in a detector can provide information on otherwise inaccessible aspects of oscillation such as the effect of traversing dense material and the variation of neutrino energy with distance traveled, over a distance range of four orders of magnitude. We describe LBNE's goals for these studies in sections 7 and 8.

4 Proton Decay Search

4.1 Scientific Interest and Goals

Free neutrons created in the lab are known to decay into a proton, an electron and a ν_e within about 1000 seconds. But is the proton stable?

Discovery of proton decay would constitute a tremendous experimental success. It is tightly coupled with the theory of Grand Unification, which proposes to unify the basic constituents of nucleons (quarks) and the non-nuclear leptonic particles such as electrons and neutrinos, as aspects of one kind of matter. Simultaneously this theory proposes a unity of three of the four basic forces—the strong, weak and electromagnetic, as mentioned in section 3.3. And contrary to the belief commonly held until the 1970s, but crucial to further testing and understanding of Grand Unification, it predicts proton decay, albeit on a timescale exceeding 10^{30} years (but not exceeding 10^{36} years) —a time- scale accessible to next-generation, megaton detectors. **FIXME:** *what about multi-hundred kt?*

A discovery of proton decay would significantly advance our understanding of Grand Unification and the matter–antimatter imbalance in the universe, and constitute a landmark discovery.

4.2 Brief History and Status

The dedicated search for proton decay began in the early 1980s. The best bounds now come from the Fréjus experiment in France; Soudan 2 and IMB in the US; and Kamiokande and Super-Kamiokande in Japan. These experiments have not seen evidence for proton decay, thus they have so far only set lower limits on the proton lifetime. The best limits (still preliminary) come from Super-Kamiokande at and Super-Kamiokande I, as shown in table 2.

Experiment	Decay Mode	τ Limit
Super–Kamiokande	$p \to e^+\pi^0$	$> 8.4 \times 10^{33}$ years
Super–Kamiokande1	$p \to K^+\bar{\nu}$	$> 2.3 \times 10^{33}$ years

Table 2: Current experimental limits on the proton lifetime.

4.3 Experimental Considerations

FIXME: *need a sentence relating necessary mass of detector to lifetime – what's needed to measure, and what's the longest tau we could measure*

Unification theories predict different values for the proton lifetime and, interestingly, different dominant decay modes, depending on the number of space-time dimensions they incorporate. Very conservatively, most four-dimensional models predict an upper bound on the proton lifetime of $\tau(p \to K^+\bar{\nu}) \leq \mathcal{O}10^{34}$ years, while for the other dominant decay mode, $\tau(p \to e^+\pi^0) \sim \mathcal{O}(10^{36})$ years. On the other hand, for Grand Unified theories in higher dimensions, $\tau(p \to e^+\pi^0)$ can be as low as 10^{33} years.

Current proton lifetime predictions up to 10^{34} years suggest that detectors need only be a factor of five to ten more sensitive than current ones to see it. The proposed water Cherenkov equivalent (WCE) detector size of several hundred kiloton should make this measurement achievable.

FIXME: *supposed to add figure I got from Milind dusel-theory/03-kearns/lyxdot. It fails. Caption reads Super-Kamiokande bounds on some prominent proton and neutron decay channels with predictions from some well-motivated theories. Courtesy of E. Kearns, NNN07 talk.*

5 Supernova Neutrino Burst Studies

FIXME: *Gina suggests an intro pgraph about snova: description, types, characteristics... I can look around, but if anybody has somewhere to point me or text to contribute, I'll take it*

FIXME: *I think this section is still too long and detailed, but want your comments*

5.1 Scientific Interest and Experimental Goals

Scientists expect supernov to occur a few times per century within the Milky Way and nearby. We are most likely to see those between 10-15 kpc from the Earth, a typical distance to stars within our galaxy. Within about 1 MPc, however, the rate increases by about a factor of thirty—to as high as one per year. A distribution of expected distances is given in reference[**?**] **FIXME:** *include table from ref Mirizzi 2006*

A core-collapse supernova releases about 99% of its energy in an initial neutrino burst that lasts a few tens of seconds, expelling about half the neutrinos in the first second. (see[**?**, **?**] **FIXME:** *add ref Scholberg:2007nu,Dighe:2008dq* for reviews) Due to the small neutrino cross section, however, we can only detect these massive neutrino bursts from supernov in our own galaxy or nearby. The neutrino energies range in the few tens of MeV, and their luminosity is divided more-or-less equally between the three flavors. The observation of 19 neutrino events in two water Cherenkov detectors for SN1987A in the Large Magellanic Cloud, 55 kpc away[**?**, **?**] **FIXME:** *add ref Bionta:1987qt,Hirata:1987hu*, confirmed the baseline model of core collapse, but leaves many questions unanswered. Through an observed high-statistics core collapse neutrino signal, we hope to learn much more in the three following areas:

- **The properties of neutrinos** Oscillations in the core can provide information on oscillation parameters, mass hierarchy and θ_{13}, possibly even down to very small values of θ_{13} inaccessible to conceivable accelerator experiments[**?**] **FIXME:** *add ref Dighe:2008dq.* **FIXME:** *say how* **FIXME:** *I don't understand this next sentence* We can mitigate supernova model- dependence of oscillation information if data from detectors at different locations around the Earth are available[**?**] **FIXME:** *add ref Mirizzi:2006xx.* Observation of a neutrino burst may also allow us to explore limits on coupling to axions, large extra dimensions, and other exotic physics. (*e.g.*[**?**, **?**]) **FIXME:** *add ref Raffelt:1997ac,Hannestad:2001jv.*

- **The astrophysics of core collapse** The time, energy and flavor distribution of the detected neutrinos can shed light on the explosion mechanism, accretion, neutron star cooling, and possible transitions to quark matter or to a black hole. An observation in conjunction with a gravitational wave detection could potentially yield dramatically improved signal-to-noise due to the coincident emission of neutrinos and gravitational waves from a supernova. (Note that not every core collapse necessarily results in a visible supernova[?]: a collapse to a black hole, for example, may produce a neutrino burst and gravitational waves but no observable electromagnetic signal.) **FIXME:** *awkward: how is osc information model-dependent?* if we can access data from detectors at different locations around the Earth [?] **FIXME:** *add ref Mirizzi:2006xx.* A neutrino burst observation will also allow us to set limits on coupling to axions, large extra dimensions, and other exotic physics (*e.g.*[?, ?]).

- **The supernova progenitor** Neutrinos emerge promptly after core collapse, in contrast to the electromagnetic radiation, which must make its way out of the stellar envelope. An early observed neutrino signal can therefore [?, ?] alert astronomers to the supernova in early light turn-on stages, which may yield information about the progenitor (in turn important for understanding oscillations).

5.2 Brief History and Status

Experimental programs initially implemented for proton decay observations have so far realized two significant successes in neutrino physics. IMB and Kamiokande made a stupendous, serendipitous discovery of supernova neutrinos in 1987, confirming the theory of supernova collapse. Super-Kamiokande has been key to understanding solar and atmospheric neutrino oscillations. **FIXME:** *(what did they discover?)*

5.3 Experimental Considerations

5.3.1 The Neutrino Interactions

From 10 kpc (the center of our galaxy), a core collapse supernova produces a few hundred neutrino (and antineutrino) interactions per kiloton in both water and liquid argon; see Table 3. The expected number of events can just be scaled by distance as $1/D^2$: see Figure **??** for 100 kt of water. In water, the dominant neutrino interaction is the inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$. There will be some charged current (CC) interactions with oxygen in water, ($\nu_e +^{16,18}\mathrm{O} \rightarrow^{16,18}\mathrm{F} + \mathrm{e}^-$, $\bar{\nu}_e +^{16}\mathrm{O} \rightarrow^{16}\mathrm{N} + e^+$). A cascade of 5-10 MeV de-excitation γ's will also tag $\nu_x +^{16}\mathrm{O} \rightarrow \nu_x +^{12}\mathrm{O}^*$ in a water Cherenkov detector [?]. Elastic scattering, $\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$, while representing only a few percent of the total signal, will allow pointing to the supernova in a water Cherenkov detector, thanks to its directional nature. It may be possible to enhance the tagging of inverse beta decay $\bar{\nu}_e$ and disentangle the flavor composition of the burst via the addition of gadolinium to the water[?], as we discuss below.

In liquid argon, a ν_e channel is available $\nu_e +^{40}\mathrm{Ar} \rightarrow e^- +^{40}\mathrm{K}^*$; the $^{40}\mathrm{K}^*$ de-excitation γ's would be observable and provide a tag[?, ?]. This specific sensitivity to ν_e will be valuable, especially for oscillation studies.

Table 3: Summary of expected core collapse signal at 10 kpc (assuming no oscillations).

100 kt water	No. of interactions
Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$	23000
CC $\nu_e +^{16,18}$ O $\to^{16,18}$ F + e$^-$	1000
NC $\nu_x +^{16}$ O $\to \nu_x +^{12}$ O*	1100
ES $\nu_{e,x} + e^- \to \nu_{e,x} + e^-$	1000
50 kt LAr	
CC $\nu_e +^{40}$ Ar $\to e^- +^{40}$ K*	12500
CC $\bar{\nu}_e +^{40}$ Ar $\to e^- +^{40}$ Cl*	260
NC $\nu_x +^{40}$ Ar $\to \nu_x +^{40}$ Ar*	15000
ES $\nu_{e,x} + e^- \to \nu_{e,x} + e^-$	500

5.3.2 Core Collapse Studies

A large detector run over a long time frame could in principle collect neutrinos one by one in coincidence with optically observed supernov [**?**]. From such data we could expect to learn more about core collapse mechanisms and supernova rates by type[**?**]. Figure 5.3.2 shows the reach of a 300 kt water Cherenkov detector. Control of background would be critical for this search given that the uncertainty of core collapse time for an optically observed supernova can be hours or more. For reference, Super–Kamiokande's remaining background for a supernova neutrino search is about 180 events per day above 7 MeV, and about 1 event per day above 17 MeV. Scaling from 22.5 kt to 300 kt mass, this gives $\sim$200 background events within a given two-hour window, and about one above 17 MeV. Addition of gadolinium, discussed below, to improve $\bar{\nu}_e$ tagging could potentially reduce this coincident background rate.**FIXME:** *by how much?*

Figure 3: Probability of detecting a burst as a function of distance. Blue: probability of two events in 20 seconds for Super-K's "distant burst search" (for an optimized energy threshold of 17 MeV) [**?**]. Red: probability of a single event about 17 MeV (solid) and a double (dashed) in a 300 kton water detector.

5.3.3 Gadolinium Doping of a Water Cherenkov Detector

Tagging the $\bar{\nu}_e$ events via their follow-on neutron captures would permit extraction of the $\bar{\nu}_e$ time structure of the supernova burst precisely, gaining valuable insight into its dynamics. Subtracting these events away from the more subtle non-$\bar{\nu}_e$ signals would uncover additional information from this once-in-a-lifetime happening. At the same time, this event-by-event subtraction would allow us to distinguish the initial $\bar{\nu}_e$ pulse from the neutronization of the infalling stellar matter, a key input in understanding supernova dynamics.

In addition, tagging the $\bar{\nu}_e$ events would immediately double the detector's pointing accuracy back to the progenitor star [?] . This is merely the result of statistics, since our elastic scatter events (about 3% of the total) would no longer be sitting on a large background in angular phase space [?]. Reducing the error on this quantity by a factor of two reduces the amount of sky to be searched by a factor of four: this could prove quite important for the narrow-field astronomical instruments simultaneously attempting to see the first light from the new supernova.

Approximately a week before exploding, a big star that is sufficiently close ($\sim$four kiloparsecs or less) would send an early warning of its impending collapse [?]. Silicon fusion would turn on in its core, raising the temperature enough that electron-positron annihilations within its volume begin to produce $\overline{\nu}_e$ just above inverse beta threshold. Although the sub-Cherenkov positrons would be invisible, the resulting neutron captures on gadolinium would result in a sudden, dramatic, and monotonically increasing singles rate, clearly indicating a coming explosion.

Gadolinium-enrichment would also make our detector sensitive to very late black hole formation following a supernova explosion anywhere within our galaxy. It would allow us to distinguish coincident inverse beta signals during the supernova's cooling phase from the usual singles backgrounds. An abrupt cutoff of these coincident signals, occurring even a few hours after the main burst, would indicate conclusively the birth of a singularity. Direct observation of such an event would clearly be of great value, especially when correlated with electromagnetic signals from X-ray or gamma-ray observatories.

6 Diffuse Supernova Background Neutrino Studies

6.1 Scientific Interest and Experimental Goals

FIXME: *from NUSAG report and Josh*

We can observe the neutrino signal of a core collapse only from within or near our galaxy. Adding neutrino fluxes of supernovae from galaxies up to the redshift of $z \sim 1$, however, would make it possible to detect a continuous Diffuse Supernova Neutrino Background (DSNB) flux. The DSNB flux depends on the redshift evolution of the supernova rate and on the neutrino emission rate and spectrum per supernova. The flux and spectrum of this astrophysical source of "relic" neutrinos thus contains information about the frequency of supernov, and consequently of star formation. Information gleaned from relic neutrinos may also shed light on neutrino properties such as mixings and the mass ordering. **FIXME:** *how?*

DSNB models vary, but according to one widely accepted modern analysis **FIXME:** *cite it* a 300 kt deep underground water Cherenkov detector doped with gadolinium should record about 50 of these supernova events every year [**?**]. This rate would allow a rapid (within two months!) discovery of the DSNB.

6.2 Brief History and Status

In its roughly five-year data set, Super-Kamiokande-I has placed a 90% confidence level limit on the flux for positron energies above 18 MeV (or relic neutrino energies above 19.3 MeV) of 1.25/cm^2-sec. The experiment found that cosmic ray muon spallation, which is depth dependent, contributes the primary background in the region 10-25 MeV . Despite identification of such radioactive background, surviving spallation events in Super-Kamiokande-I still overwhelm the expected supernova relic neutrino interaction rate below this energy. Super–Kamiokandehas therefore limited its search to above 18 MeV positron energy (or 19.3 MeV relic neutrino energy) and placed a 90% confidence level limit on the flux above that of 1.25/cm^2-sec.

6.3 Experimental Considerations

Positrons resulting from the inverse β reaction with electron antineutrinos ($\bar{\nu}_e$) provide the best signal for relic supernova neutrinos in water Cherenkov detectors. We show the predicted spectrum and event rate of the relic antineutrinos in Fig. 4. While the maximum flux occurs at lower energies (< 5 MeV), 10 MeV marks the practical lower limit for detection of positrons from this interaction. Below that, antineutrinos from nuclear power reactors raise the background.

For a 300 kt water Cherenkov detector, we estimate a possible positron energy threshold of 15.5 MeV, **FIXME:** *how does energy threshold depend on detector size?* and sensitivity of < 0.3 cm^{-2}sec^{-1}to the 90% CL at the 4850 ft. depth. This is below the predictions in [**?**]. At 15.5 MeV, a Gadolinium-doped

WC detector would exhibit sensitivity well below the predicted relic supernova neutrino flux.

For a liquid argon detector, the detection mechanism is different and we expect its fine granularity to reduce backgrounds significantly.

Water Cherenkov and liquid argon detectors are highly complementary for the detection of relic supernova neutrinos. Water Cherenkov detector detects $\bar{\nu}_e$ while liquid argon detector detects mainly ν_e events. A combination of the two would allow important checks on our understanding of astrophysics as well as neutrino properties.

Figure 5 shows the expected relic supernova neutrino signal [**?**] with backgrounds from solar neutrinos at low energies and from atmospheric neutrinos at higher energies. It includes effects of energy resolution ($\sim 4\%$ at 10 MeV) [**?**]and effects of oscillations that are expected to enhance the rate for ν_e. The sensitivity depends strongly on the choice of signal window. From the figure, it is clear that 16 to 40 MeV offers the best window for identifying the signal above background. Integrating this signal window for five years of data taking with a 100 kt liquid argon detector yields 57 ± 12 events [**?**].

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As discussed in section 2.4.1, the introduction of a water-soluble gadolinium compound potentially offers a significant neutron-capture enhancement to a large water Cherenkov experiment. The inverse beta decay reaction (see equation 2.4.1) in a Gd-enriched detector will yield coincident positron and neutron capture signals as long as the detector can record five or more photoelectrons per MeV. Once we can detect coincident signals, then troublesome spallation backgrounds can be essentially eliminated, and the DSNB analysis threshold will fall far below the traditional 19 MeV cutoff. A lower energy threshold of 10 MeV increases the predicted flux by a factor of 2.3, so using a neutron tag and lowering the threshold could provide excellent sensitivity even at depths shallower than Super-Kamiokande. This will not only allow detection of the so-far unseen DSNB flux, but it will also allow us to extract important—and unique, barring a galactic supernova—information regarding the neutrino emission parameters of supernov.

7 Solar Neutrino Oscillation Studies

7.1 Scientific Interest and Goals

The deficit of observed electron-neutrinos from the sun compared to expectations, a decades-old puzzle, has been definitively explained as due to the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism, also called the *matter effect*. **FIXME:** *ref* In this effect, the flavor content of a neutrino beam changes as it traverses the sun, due to the difference between the forward scattering amplitude of electron-neutrinos and that of the other flavors within the solar volume.

Observation of a change in the flavor content of a single neutrino beam with and without intervening matter would provide the most direct and convincing demonstration of the matter effect. The solar ^{8}B **FIXME:** *what's this symbol supposed to be?)* neutrino beam provides just such a possibility: at night, any detected neutrinos from the sun would have passed through the dense core of the Earth, during the day they would come directly from overhead. As the beam from the sun arrives at the Earth, it is nearly a pure ν_2 state and therefore its flavor content is only $\sim$1/3 ν_e. After traversing the Earth, we expect a net gain in ν_e content. We call this the —em day-night ν_e flux asymmetry.

Given sufficiently good energy resolution **FIXME:** *quantify, and compare to our detector design* in a detector, we could measure the solar *hep* flux (the solar neutrino flux component expected to have the highest energy is about 1/2000 of the ^{8}B flux. We might also set limits on the flux of solar antineutrinos and the neutrino magnetic moment if backgrounds are small enough.**FIXME:** *AH: quantify– maybe in depth doc?* These measurements are not as high-priority as the day-night measurement and they are noticeably more vulnerable to spallation backgrounds, however a detector at a depth of at least 4300 mwe may make them possible.

FIXME: *how big is this signal and what statistics are needed?*

7.2 Brief History and Status

The first oscillation parameter values (see the current values in table 1) came from measurements of solar and reactor neutrino oscillations. The positive sign of Δm^2_{21} in fact follows from the effects of the solar medium on the propagation.**FIXME:** *how?*

Over the past few years, the Sudbury Neutrino Observatory (SNO) and the Super-Kamiokande Collaborations have studied in great detail neutrinos from ^{8}B decay within the sun. With the additional reactor antineutrino disppearance measurements by the KamLAND collaboration, it has become clear that at energies above 1 MeV, solar neutrino flavor transformation is dominated by the matter effect.

7.3 Experimental Considerations

The best fit values of the mixing parameters indicate the largest day-night ν_e flux asymmetry at energies higher than 5 MeV. A large detector **FIXME:** *quantify* with reasonable light collection ($\sim 30\%$ coverage with photocathode of 20% quantum efficiency) can access energies as low as 7 MeV without special requirements on the purity of detector materials. Figure 6 shows the solar ν_e survival probability as a function of energy, for both 'day' and 'night' neutrinos, for the central large mixing angle region. Here we will assume an analysis cut at 7 MeV, above which radioactive background becomes unimportant, leaving only spallation events as significant.

A measurement of the day-night asymmetry can take several forms. At its simplest, we can define an integral asymmetry measurement (A) as:

$$A = \frac{2(\phi_{\nu_e}^{night} - \phi_{\nu_e}^{day})}{\phi_{\nu_e}^{night} + \phi_{\nu_e}^{day}} \tag{2}$$

Currently, the Super–Kamiokandeand SNO Collaborations measurements on this integral asymmetry have found $A = 0.021 \pm 0.02^{+0.013}_{-0.012}$ [**?**]

FIXME: *"smy" and "nsp" are the bib refs to find*

and $A = -0.037 \pm 0.063 \pm 0.032$ [**?**], respectively, each within 1σ of $A = 0$ when both statistics and systematics are included. For a 300 kTon water Cherenkov detector, the event rate in the detector would be roughly 130/day, and consequently the statistical precision on this asymmetry after a year should be significant, namely ~ 0.005, assuming an achievable analysis energy threshold of 7 MeV.

Event Category	SK (172 kton-year)	1 Mton-year
Sub-GeV e-like 0-decay	5687	33000
Multi-GeV e-like	2345	13600
Multi-Gev μ-like	2523	14600
Partially-Contained	1671	9700
Upward-going μ	4242	24600

Table 4: Simple scaling of the Super–Kamiokandeevent rates [83] to a 1 Mton-year exposure. The Multi-GeV e-like and μ-like numbers include single- and multi-ring events.

For the current best fit LMA parameters, we expect the integral asymmetry to be near 0.02. More sophisticated analyses**FIXME:** *references?*, involving fits to the energy and zenith angle-dependent survival probabilities, have already provided noticeably better measurements of the asymmetries in both Super–Kamiokandeand SNO, and could be applied in a larger detector as well.

8 Atmospheric Neutrino Studies

8.1 Scientific Interest and Goals

FIXME: *Maury asks: do we want the theta 1-3 focus up front? Ask Chris Walter and Roger Wendell*

Products of decays from secondary particles, atmospheric neutrinos are generated by high-energy cosmic rays in a uniform spherical thin shell in the Earth's upper atmosphere. Atmospheric neutrinos are well suited to neutrino oscillation studies because their isotropic flux consists of neutrinos whose path lengths span four orders of magnitude, from $\sim$ O(10) km to $\sim$ O(10^4) km. Coupled with their similarly wide energy spectrum (100 MeV to $\sim$ 1 TeV) they are a particularly useful probe of the L/E (length vs energy) dependence of standard neutrino oscillations **FIXME:** *what's a 'standard' osc vs just an osc?*. Current solar neutrino data indicate that matter-modified neutrino oscillations exist (i.e., the MSW or*matter effect* is real; see 7.1) and should therefore be observable in atmospheric neutrino oscillations, as well, through the 'day-night' effect.

The detection and study of atmospheric neutrinos **FIXME:** *add ref of Super–Kamiokande1998* have in fact resulted in the discovery that muon-type neutrinos impinging from below the detector, after coming through the Earth, are suppressed by a factor of $\sim$2 compared to those that come from above. This effect is coupled to the value of θ_{13}; if θ_{13} is near the Chooz limit of $\sin^2 2\theta_{13} < 0.02$, the transition probability may be high enough that we can constrain or even measure this angle. Further, the effect is sensitive to the neutrino mass hierarchy. Since the sign of the mass hierarchy differs between neutrinos and anti-neutrinos, under the normal hierarchy, only neutrinos will experience the resonance **FIXME:** *clarify "the resonance"*. Accordingly, under the inverted hierarchy only antineutrinos will. Provided θ_{13} is large enough **FIXME:** *over what value, the Chooz limit?*, we can use atmospheric neutrinos to help determine the sign of the hierarchy.

This study will help us to improve the precision on the mixing parameters and to search for new effects that could become accessible from higher statistics. Larger detectors have in fact provided an increase in statistics**FIXME:** *ref*, and this has been matched by greater accuracy of simulations of the atmospheric flux **FIXME:** *ref.*

8.2 Brief History and Status

The Super-Kamiokande experiment's atmospheric neutrino sample has been collected over a period of more than ten years. High statistics and low backgrounds have yielded a rich data set that has probed much of neutrino oscillation physics. Under the standard two-flavor oscillation model the Super–Kamiokandedata are best fit to maximal mixing, $\sin^2 2\theta_{23} = 1.0$ and $\Delta m^2_{23} = 2.1 \times 10^{-3}\text{eV}^2$. These data are inconsistent with oscillations into a sterile neutrino and have shown that the ν_μ disappearance can be attributed to conversion into ν_τ. Analyses that include all active neutrino flavors can extend the reach of atmospheric neutrinos further.

8.3 Experimental Considerations

Using a 172 kt-year exposure, the Super–Kamiokandecollaboration has explored these physics topics and constrained the atmospheric mixing parameters to $1.8\times 10^{-3} < \Delta m^2_{32} < 2.6\times 10^{-3}\mathrm{eV}^2$ and $0.95 < \sin^2 2\theta_{23} \leq 1.0$ [82]. **FIXME:** *make sure kajita 09 ref is in bib* In subsequent analyses the value of $\sin^2\theta_{13}$ is constrained to be less than 0.04 with no evidence of a preferred **FIXME:** *mass?* hierarchy [83]. Assuming similar systematics at a 100 kt detector, a Super–Kamiokande-sized data set could be reproduced in less than two years and provide a similar physics impact.

Extrapolating the Super–Kamiokandedata to a 1 Mton-year exposure yields the event rates in table 4. **FIXME:** *not sure I got the next sentence right* The high-energy, fully contained, μ-like data and the partially contained data provide the basis for the Super–Kamiokandedisappearance result with a strong contribution to the size of the allowed Δm^2 region coming from the upward-going muon sample. Sensitivity to non-zero θ_{13} and the mass hierarchy comes predominantly from a only a handful of bins in the Multi-GeV electron samples. Despite reasonable statistics in the sample as a whole, the sensitivity could be improved by increased statistics in these comparatively sparsely populated bins. Expected sensitivities to the atmospheric oscillation parameters for a 1 Mton-year exposure are shown in Tbl. **??**. **FIXME:** *I have to look for this table*

It has also been shown that kinematic reconstruction of the outgoing proton in neutrino interactions is possible[86] and can be used to form a nearly pure charged current quasi-elastic (CCQE) sample. **FIXME:** *what is significance of ccqe?* For a 1 Mton-year (10 years at 100 kt) exposure, we expect between 700 and 800 tagged CCQE events[85] **FIXME:** *in order to determine/constrain xyz.* Furthermore, the low amount of anti-neutrino events in these samples could be used as an additional handle on studying hierarchy effects.

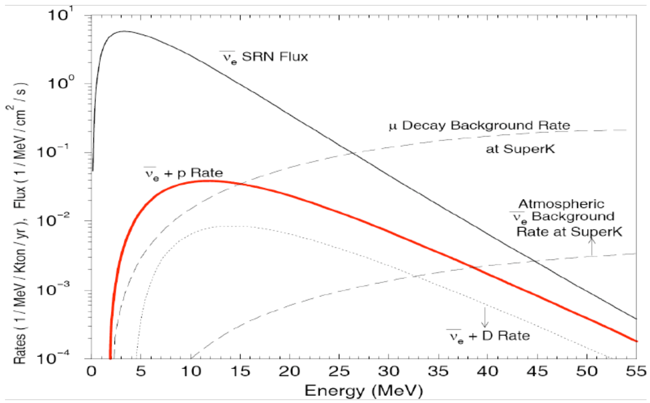

Figure 4: (in color) Flux of relic supernova neutrinos (solid $\bar{\nu}_e$). The rate of $\bar{\nu}_e$+p events (dashed). Rate of muon decay and atmospheric neutrino backgrounds (long dashes). And the rate of $\bar{\nu}_e$ absorption on deuterium for comparison (dotted). [?]

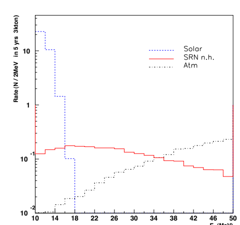

Figure 5: Number of expected events for relic supernova neutrinos and backgrounds, assuming 100% detection efficiency for electrons with energy greater than 5 MeV, per year, for a 3kton detector [?].

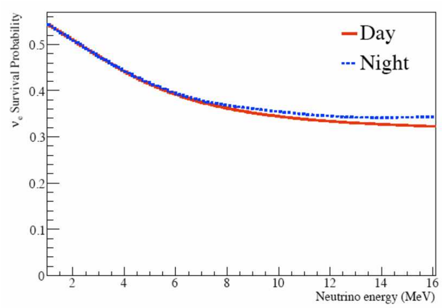

Figure 6: Electron neutrino survival probability as a function of energy, for day and night [?].

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